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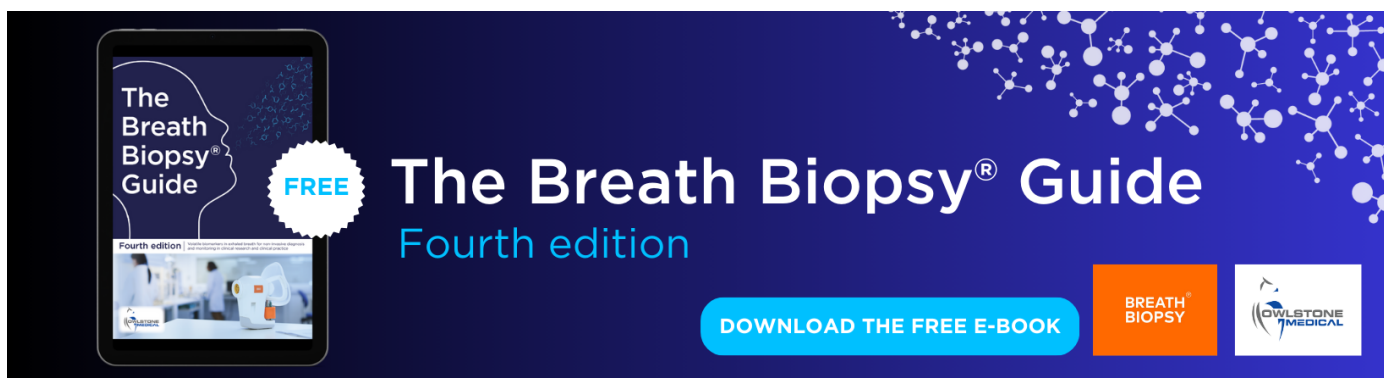# The impact decades-long dependence on hydropower in El Niño impact-prone Zambia is having on carbon emissions through backup diesel generation

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LETTER

The impact decades-long dependence on hydropower in El Niño impact-prone Zambia is having on carbon emissions through backup diesel generation

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Abstract

Emissions associated with hydropower are often forgotten. Lifecycle assessments of greenhouse gas emissions emanating from hydropower must count embedded carbon, emissions from reservoir lakes and the loss of carbon sinks, as well as backup diesel generation emissions when dependence on hydropower fails to deliver energy. Using Zambia as a case study, we estimate using a bottom-up approach that the emissions associated with backup diesel generation from Zambia's power utility ZESCO and three largest sectors of consumers were up to 27 000 tonnes of CO_2 in the worst months of drought in 2019. This is significantly higher than what a previous top-down approach would have estimated.

We worked out ZESCO's diesel generation attributable to drought using trend analysis. We worked out the mining sector's emissions using copper production data, on-grid electricity consumption and calculated electricity intensity to infer off-grid electricity consumption in years of drought. From our household survey we learned average duration of generator use, average capacities of generators and acquired household income and generator use data which we ran in a Tobit regression. These together with labour force survey data helped us infer the level of diesel generation by households of different income brackets. For manufacturing firms we surveyed 123 firms. We collected rich diesel generation use data covering years of drought, input this into an OLS regression to identify predictors of diesel generation use (installed capacity of generator in kVA, in litres and whether generation was in a drought year) which we then used to extrapolate implied diesel generation for the firms for which we had less rich data.

As global average temperatures and the frequency of El Niño droughts rise in hydropower dependent countries which account for a fifth of the world's population, backup generation emissions have implications for the formulation of low carbon energy policy.

1. Introduction

Looking at proposed hydropower dams and the associated distribution infrastructure required in Chilean Patagonia, Mar (2009) forecast that the carbon impact of construction equipment and machinery, transport of labour, material embedded energy, and land-use change would be 48x the impact of natural gas plants that would deliver an equivalent amount of energy. Reservoirs themselves contribute to 1.5% of global anthropogenic emissions from carbon dioxide,

methane, and nitrous oxide reported by the UN Intergovernmental Panel on Climate Change (Deemer *et al* 2016). On top of that, hydropower dependency can also lead to the release of greenhouse gas emissions in another way: when rainfall is low, hydropower ceases to be the dependable source of energy that the grid operator has used it for, and end-consumers (and even the power utility itself) resort to generating their own energy using diesel generators.

Farquharson *et al* pioneered thinking about the implications of electricity outages in sub-Saharan

Africa for CO_2, SO_x and NO_x emissions from diesel generators (Farquharson *et al* 2018). However, their top-down approach as well as their outdated data have underestimated the significance of emissions from backup diesel generation. This study aims to highlight the significance of backup diesel generation emissions in a hydropower dependent context using recent data and a bottom-up approach with Zambia as a case study.

2. Background

World Bank data (2020a) show that there were at least 58 countries as of 2015 that were more than 25% reliant on hydropower for domestic electricity production.[3] Among these countries, 33—whose combined population accounts for almost a fifth of the world's population—have been affected by droughts attributable to the El Niño effect. El Niño events have been forecast to increase in frequency with global warming (Wang *et al* 2017). This will necessitate the governments and power utilities of those countries, largely located in southern Africa, southeast Asia, Australasia, and northern South America (FAO 2015, 2018, Vidal 2016, Hao *et al* 2018), to think about how to make their energy generation infrastructure more climate resilient. It will also necessitate thinking on how to avoid contributing to the global warming that is making their hydropower infrastructure increasingly redundant. We show that unreliable hydropower infrastructure paradoxically results in increased purchases and use of high-greenhouse gas emitting diesel generators.

We took Zambia as our case study. As of 2015, Zambia was one of at least 12 countries, of which 11 were not high-income countries, that were more than 80% reliant on hydropower for their electricity production (Zambia was at that time 97% dependent), while at least 35 countries, of which 26 were not high-income, were more than 50% reliant on hydropower (World Bank 2020a, 2020b).

For decades, using hydropower as a dispatchable source of energy was not the reason why Zambia's power utility ZESCO sometimes failed to deliver energy reliably, since energy supply with properly maintained infrastructure would have far outstripped demand. But then:

1. Demand caught up with supply. By 2015 electricity demand was 1959 MW, compared with installed capacity of 2411 MW (email sent by an energy officer at the Ministry of Energy on 30 April 2020); average capacity only needed to fall below 81% for Zambia to experience power outages.

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[3] Information was not given for all countries such as Uganda and the Southern African Power Pool countries Lesotho and Swaziland.

2. Energy supply dipped. Low levels of rainfall (World Bank 2018b) resulted in lower reservoir levels in Zambia's hydropower dams (interviews with ZESCO Ltd staff, 10 November, 2017 and 6 June, 2018). The result was load shedding lasted a minimum of 8 h a day for the majority of ZESCO's customers (Energy Regulation Board of Zambia 2016, p 1). Less energy was consumed in Zambia in 2015 than was consumed in 2014 and less energy was consumed in Zambia in 2016 than was consumed in 2015 (Energy Regulation Board of Zambia 2016, 2018, Zambia 2017). While 2017 and 2018 saw rainfall levels recover, December 2019 saw Kariba Dam's reservoir level fall to 9% capacity from 76% in September 2018 (Malunga 2019, Zambezi River Authority 2019). Kariba Dam constituted 37% of Zambia's installed power capacity (Energy Regulation Board of Zambia 2019).

Due to the El Niño effect, low rainfall in 2015 and 2016 resulted in low reservoir levels that forced Zambia's power utility ZESCO to enact load shedding across the country lasting a minimum of 8 h a day (Energy Regulation Board of Zambia 2016, p 1). Then again in 2019 the low reservoir levels resulted in power outages, this time lasting up to 15 h a day (Zesco 2019). The power deficit reached a high of 1000 MW in 2015 and reduced to 526 MW in 2016 (Energy Regulation Board of Zambia 2017, p 15). The effect was that electricity-intensive manufacturing, a traditional catalyst for industrial-led economic growth (Szirmai and Verspagen 2015, Cantore *et al* 2017), lost not only production potential in 2015 and 2016—when its absolute electricity consumption fell below its 2014 level—but that by 2017 it had also lost relative electricity consumption share to finance and property (see table 1).

Had ZESCO not mitigated its generation shortfall with additional diesel generation and more importantly the import from the Southern African Power Pool (SAPP) of 785.2 GWh in 2015 (up from just 12.8 GWh in 2014) and 2184.9 GWh in 2016 (ibid, p9), the deficits would have been even greater. Grid electricity consumers also turned to alternative generation strategies.

Figure 1 below illustrates Zambia's electricity and electricity substitute systems boundary. It builds upon Bayliss and Pollen's system of provision (Bayliss and Pollen 2019, figure 1) which was limited to grid electricity consumption. This system includes the 77% of the population that live without grid connections (ZICTA and CSO 2018) and who rely on off-grid solutions including solar products and biomass (Tembo 2018) 50 years after the World Bank's substantial energy investments into Zambia (World Bank 2018a) to support mining (IBRD and IDA 1970, 1973) in the vain hope that the benefits of

Table 1. National electricity consumption by economic sector, 2014–2018. Reproduced with permission from Ahmed *et al* (2019).

Sectors	2014		2015		2016		2017		2018	
	GWh	% share	GWh	% share	GWh	% share	GWh	% share	GWh	% share
Mining	5871	47.3%	6246	54.5%	5918	54.5%	6202	50.9%	6682	54.8%
Domestic	3251	26.2%	3482	30.4%	3383	31.2%	4147	34.0%	4337	35.6%
Finance & property	487	3.9%	517	4.5%	499	4.6%	640	5.2%	714	5.9%
Manufacturing	479	3.9%	**531**	**4.6%**	**470**	**4.3%**	503	**4.1%**	593	**4.9%**
Agriculture	241	1.9%	260	2.3%	228	2.1%	262	2.1%	297	2.4%
Others	99	0.8%	99	0.9%	80	0.7%	87	0.7%	84	0.7%
Trade	107	0.9%	110	1.0%	97	0.9%	110	0.9%	114	0.9%
Energy & water	73	0.6%	89	0.8%	88	0.8%	81	0.7%	69	0.6%
Quarries	62	0.5%	68	0.6%	60	0.5%	118	1.0%	148	1.2%
Transport	31	0.3%	33	0.3%	28	0.3%	32	0.3%	33	0.3%
Construction	1702	13.7%	15	0.1%	7	0.1%	10	0.1%	11	0.1%
Total	**12 405**	**100%**	**11 450**	**100%**	**10 857**	**100%**	**12 192**	**100%**	**13 080**	**107%**

Sources: Energy Regulation Board of Zambia (2016, p 0, 2017, p 9, 2018, p 36), 2019, p 39).

hydropower would trickle down (Park 1968). Personal interviews with Africa GreenCo (4 June 2018, 23 April 2019, 3 September 2019) revealed that the company intends to facilitate investment into renewable Independent Power Projects by becoming a private credit-worthy off-taker that on-sells to ZESCO, to clients on the SAPP and to bilateral clients. Agricultural firms can meet their electricity needs using their biomass (Sugar 2017, p. 15). Manufacturing firms use backup diesel generation to make up for lost ZESCO power (Ahmed *et al* 2019), as do mining companies (Mfula 2010a, 2010b, News 2011, Syndigate 2011). Grid-connected households' favourite mitigation strategy to power outages is rechargeable lights and solar products; 10th and 11th favoured strategies are UPSs and diesel generators (Ahmed 2020).

Our earlier findings that manufacturing firms and households self-generate energy using diesel to the extent that they do (Ahmed et al 2019, Ahmed 2020) motivated this study whose aim is to quantify and aggregate the CO_2 emissions from diesel generation by ZESCO as well as Zambia's three largest types of electricity customer at the advent of its first set of power outages in 2015: mining companies, households and manufacturing firms.

3. Methods

We adapted our approach according to the homogeneity of a sector and, for the sectors where we collected data from respondents, the granularity and verifiability of data available. The Energy Regulation Board of Zambia provided diesel generator use by the power utility ZESCO. Using trend analysis we worked out the difference of ZESCO's diesel generator use between years when there was no load shedding and years in which there was load shedding due to low hydropower reservoir levels. Because mining is a fairly homogenous sector (explained further

below), we relied on existing secondary data from the Energy Regulation Board for the sector's on-grid electricity consumption and the US Geological Survey for production and broad assumptions about production (see table 2 above). Broad assumptions would have been unsafe for households and the manufacturing sectors which are a lot more diverse. For this reason, we collected primary data for these sectors. Nine manufacturing firms recorded the litres of diesel fuel that they consumed, installed capacity of their generators and the hours that they ran their generators for, while 84 of the 91 firms that reported using self-generation that we interviewed provided some of this data. We were thus able to extrapolate fuel use by the sector using OLS regression analysis with a strong degree of confidence. For households we found income to be a statistically significant predictor of generator use and ownership, and we therefore extrapolated fuel use using this relationship.

3.1. ZESCO's diesel generation

To make up for the energy shortfall during the power outages of 2015 and 2016, ZESCO resorted to generating energy from its diesel power plants. We used Energy Regulation Board reports of ZESCO backup diesel generation use from 2008 to the most recently available year to work out changes in diesel generation, which in turn helped us to work out the extent of diesel generation in 2015 and 2016 that was attributable to the hydropower dams not being able to generate sufficient energy in those years.

We calculated diesel generation attributable to drought over a year by ZESCO (ZESCO DGD) as

$$ZESCO\ DGD = DGYD - DGPD$$

where DGYD is diesel power generation in year of drought, GWh.

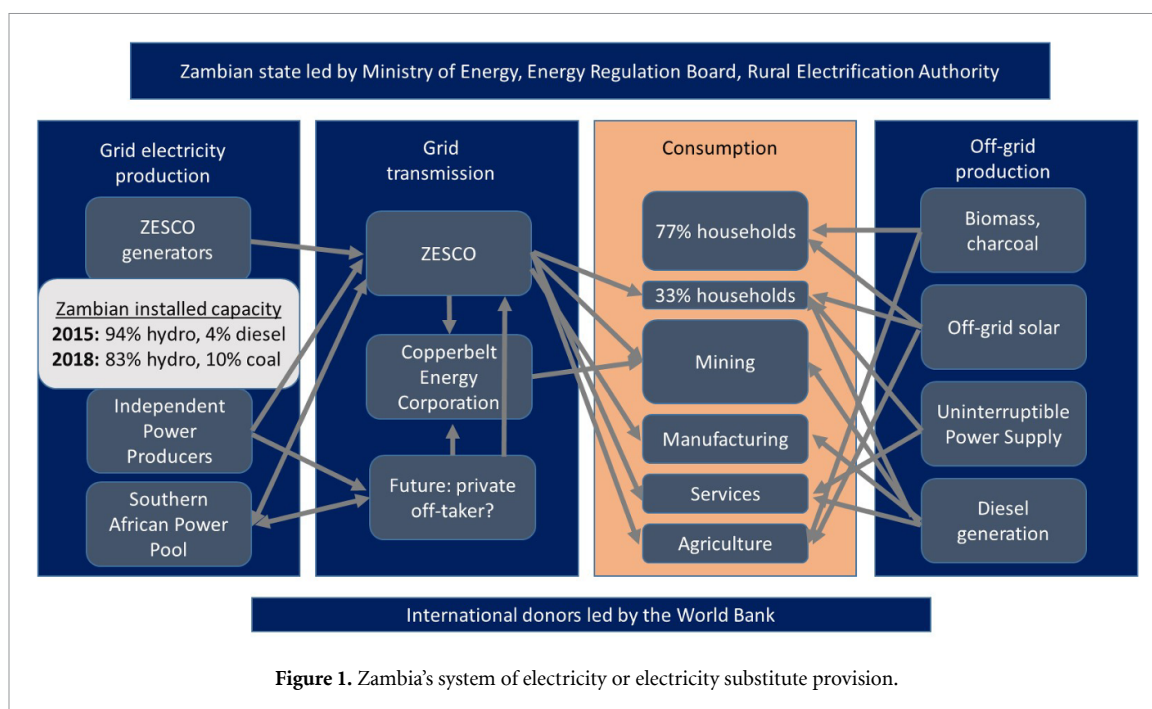**Figure 1.** Zambia's system of electricity or electricity substitute provision.

Table 2. Our broad assumptions. Reproduced with permission from Ahmed *et al* (2019).

Agent	Alternatives to diesel generators	Marginal costs of diesel generated pollution or GHG emissions	Electricity intensity of production (kWh/'000 tonnes)
Firms	Other off-grid solutions: Shut down: - Solar PV - Biomass - Industrial waste - Reschedule operational hours - Not make up for lost hours	Do not incur these costs	Does not vary.
Households	Uninterruptible power supply (UPS) to dispense stored energy to electrical appliances Off-grid products (off-grid lights, laptop batteries, mobile phone external battery packs)	Suffer from the noise May suffer from the pollution	Has room to vary as individuals can move to locations with electricity.

And DGPD is diesel power generation in last year prior to drought, taking into account growth of use of diesel generation, GWh.

From diesel generated energy attributable to the drought, we worked out the implied CO_2 emissions using publicly available conversion rates.

3.2. The mining sector

Although mining is by far the largest electricity consumer in Zambia, we anticipated that it would also be the least diverse in terms of its energy use patterns among ZESCO's clients. Most of Zambia's mining is for copper[4], and 80% of Zambia's copper comes from just four mines (Zambia Chamber of Mines 2016).[5]

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[4] Copper and copper products accounted for 92% of Zambia's exported metals by value in 2018 and 72% of all exports (World Bank 2020a).

[5] The Lumwana and Kansanshi mines are open pit (Barrick Gold Corporation 2019, First Quantum Minerals Ltd 2019), whereas Mopani and Konkola Copper are a mix of underground and open pit mines (Konkola Copper Mines Plc. 2019, ZCCM Investment Holdings Plc 2019).

Table 3. Data used for each genre of agent considered and calculations made to calculate diesel generation. Reproduced with permission from Ahmed *et al* (2019).

Agent	Data	Sampling achieved
ZESCO	Secondary: Energy Regulation Board reports	N/A
Mining companies	Secondary: Energy Regulation Board reports, US Geological Survey	N/A
Households	Primary: In person surveys Secondary: 2012 Labour Force Survey	Snowball effect: 54 online responses from emails and social media to contacts and their contacts collected from around Zambia, concentrated in Lusaka, 47 responses after cleaning the data of student responses. The survey duration was cut short to a month due to electricity tariffs changing on 1st January 2020 which affected another part of the survey.
Manufacturing firms	Primary: Online household surveys	Stratified, representative sampling achieved by subsector of 123 manufacturing firms located in Zambia's main manufacturing hubs Lusaka in Lusaka Province and in Ndola and Kitwe in Copperbelt Province

Both open pit and underground mines use diesel generation to prevent ZESCO power outages from resulting in loss of production (Mfula 2010a, 2010b, News 2011, Syndigate 2011), although underground mines are more electricity intense (Tembo 2018, p 41). Use of generators by the mining sector preceded the El Niño droughts of 2015 and 2016; mines experienced power outages for various reasons, ranging from apparent vandalism to fires damaging ZESCO equipment (Jourdan 1990, Mfula 2010a) (also email dated 17 February 2019 from Michael Mainelli, assigned to advise on the privatisation of Zambia Consolidated Copper Mines in 1992).

To calculate the emissions emanating from the sector, we looked to the average historic energy intensity associated with mining production in years prior to 2015 to impute what level of electricity production (both on and off-grid) would have been required to extract that which was mined in 2015 and 2016. The difference between this value and the on-grid energy consumption of the sector would tell us what the sector likely consumed from off-grid backup diesel generation.

We calculated diesel generation attributable to drought over a year by the mining sector (Mining DGD) as

$$\text{Mining DGD} = \text{Mining EI} \times \text{Cu} - -\text{Mining GE}$$

where Mining EI is average electricity intensity of mined copper, GWh/'000 tonnes.

Cu is copper mined over the year, '000 tones.

Mining GE is grid electricity consumed by the mining sector over the year, GWh.

From diesel generated energy attributable to the drought, we worked out the implied CO_2 emissions using publicly available conversion rates.

3.3. Households

We now turn to the second largest consuming sector of electricity in Zambia: households. The Zambia Information and Communications Technology Authority and Zambia's Central Statistical Office estimated that in 2018, Zambia had a population of 16.9 million people across 3.5 million households, grid energy access of 33%, and internet access of 18% (ZICTA and CSO 2018). This implies that 630 000 households had internet access.

After obtaining ethical approval from University College London, we collected surveys from 54 individuals online in December 2019.[6] We shared the survey with our personal contacts by email, WhatsApp, LinkedIn and Twitter, and requested these contacts to share the survey with their contacts. Although 128 surveys were initiated, the majority did not sign the ethical permissions required to proceed with answering the survey questions. We stopped the survey within a month because of a regulatory

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[6] The data that support the findings of this study are available at https://imadahmed.com/2020/07/26/erl-diesel-emissions-data/. Full survey data and questionnaires will be made available upon the publication of another journal article and Imad Ahmed's PhD.

change in tariffs which we believed would contaminate the results of the rest of our survey questions. 83% of respondents answered from Lusaka Province and 9% from Copperbelt Province. There was one respondent (1.8% of respondents) for each of four other provinces: Muchinga Province, Easter Province, Southern Province and Luapula Province. The sample collected therefore overrepresented Lusaka by 2.2x in terms of active internet users, underrepresented the Copperbelt by 1.7x, and underrepresented Southern Province by over 30 times. Together, these three provinces accounted for 71% of Zambia's active internet users (ZICTA and CSO 2018, figure 79). Had data existed on the total residential-use data purchased disaggregated by province, the sampling achieved may not have been so over-weighted for Lusaka.

Each respondent used a distinct internet protocol address. Between this and the fact that no two set of responses was alike, it is likely that each response represented a distinct household. We asked respondents whether they owned generators, to what extent they used generators, their income brackets, and their ages. Where we found respondents to be aged 25 or less and in the lowest income brackets, we discarded their responses as those who were 25 or younger and in the lowest income bracket and were using generators may have been doing so with support from their parents, and so should have been counted in their parents' households, or were getting the benefit of diesel generators thanks to their university accommodation—the survey had reached University of Zambia students. These under 25 year olds would not have been representative of the Zambian population. We cleaned the data for these 25-year olds, who accounted for 7 of the 54 responses.

We calculated diesel generation over a month by households following these steps:

1. We asked households which monthly income bracket they fell into and how much they used their generators on a scale of 0 to 4.[7]
2. We ran a Tobit regression with generator use as the dependent variable and household income as the independent variable.
3. To get relative generator use intensity for each household income bracket (RI), we a. multiplied the statistically significant coefficient by each household income bracket b. divided each intensity score by the highest intensity score (scored by the highest income bracket since the coefficient was positive).
4. We then calculated diesel generation by households over a month (HH DG) as

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[7] Respondents rated their use of energy generated using diesel on an ordinal categorical scale of 0 to 4 with 0 signifying 'do not use', 1 signifying 'use a bit', 2 'use to a moderate extent', 3 'use to a major extent' and 4 signifying 'rely upon all the time'.

$$\text{HH DG} = \sum_{LIB}^{HIB}(\% \ UG_{IB} * \#HH_{IB} * \ RI_{IB} * DU * C * 30)$$

Where IB is income bracket

HIB is highest income bracket

LIB is lowest income bracket for which data was collected

$\%UG_{IB}$ is use of generators per household income group

$\#HH_{IB}$ is number of households in income bracket

RI_{IB} is relative generator use intensity for each household income bracket

DU is average daily use, hours

C is average generator capacity, translated into kW

30 is average days/month

From diesel generated energy, we worked out the implied CO_2 emissions using publicly available conversion rates.

3.4. Manufacturing firms

Unlike copper mining which is dominated by four mining companies and mining pits in Zambia, the manufacturing sector is diverse. In the capital Lusaka, the Ministry of Trade and Commerce noted over 80 types of manufacturers (Ministry of Commerce Trade and Industry 2014, pp. 133–139). Load shedding in Zambia seems to have different impacts on different manufacturing subsectors (Sichone *et al* 2016); diesel generator use also seems to vary across Africa by subsector (Steinbuks and Foster 2010).

To collect firm-level data on generator usage, we hired a team of enumerators through funding made available by the International Growth Centre and managed to survey 123 firms between April-August 2018 in Zambia's largest manufacturing hubs: Lusaka, and Ndola and Kitwe in the Copperbelt Region. We wanted to collect data on capacity of generators used in terms of kVA and litres, usage data varying between drought and non-drought years and varying with manufacturing subsector, year of purchase of first generator, losses experienced as a result of power outages and the extent to which firms successfully mitigated these (Ahmed *et al* 2019). We aimed to survey a representative sample of Zambia's large manufacturing firms by subsector and by geographic industrial hub. To do this, we studied the national breakdown of manufacturing subsectors according to the latest census data we were able to find (Ministry of Commerce Trade and Industry 2014). In this regard, we succeeded. In our sample, no subsector was over or underrepresented by more than 9% (see table 4). With regards to sampling by representative geographic hubs, we under surveyed in Kitwe and Ndola in the Copperbelt Province. We aimed to have 59% of the sample come from Lusaka and the remaining from the Copperbelt (since 50% of large manufacturing firms are in Lusaka and 84% of large firms are

Table 4. Sampling achieved by subsector vs national population of large manufacturing firms by subsector.

Subsector	Lusaka & Copperbelt	Central	Eastern	Luapula	Muchinga	Northern	NW	Southern	Western	Total	National	Achieved sample	Delta
Food and food products	96	7	6	2	1	7	3	15	2	139	36%	39%	−3%
Textiles and garments	15	0	2	0	0	0	0	1	0	18	5%	9%	−4%
Wood and wood products	21	0	0	0	0	0	1	2	1	25	6%	3%	3%
Chemicals	48	2	0	0	0	0	0	1	0	51	13%	16%	−3%
Plastics and rubber	25	1	0	0	0	0	0	0	0	26	7%	16%	−9%
Non-metallic mineral products	30	1	0	0	0	0	0	0	0	31	8%	1%	7%
Basic metals	19	2	0	0	0	0	0	1	0	22	6%	8%	−2%
Fabricated metal products	27	2	0	0	0	0	0	0	0	29	7%	12%	−5%
Machinery and equipment	28	0	0	0	0	0	2	0	0	30	8%	1%	7%
Electronics	10	0	0	0	0	0	0	0	0	10	3%	0%	3%
Other manufacturing	10	0	0	0	0	0	0	0	0	10	3%	0%	3%
Total	**329**	**15**	**8**	**2**	**1**	**7**	**6**	**20**	**3**	**391**			

Table 5. Calculating ZESCO generated energy from diesel energy had there not been power shortages from hydropower in 2015 and 2016.

Row	Year	Conversion factor	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	Total diesel generation by ZESCO diesel power plants, GWh		8.3	9.1	10.3	11.9	12.2	16.8	15.7	8.7	4.5
2	*Growth rate*			*10%*	*13%*	*16%*	*3%*	*38%*	*−7%*	*−45%*	*−48%*
3	*Compounded average growth rate, 2010–2014*		*10%*								
4	Predicted diesel generation in 2015, 2016 based on previous CAGR, GWh							13.4	14.8		
5	Implied excess demand as a result of power shortages, GWh							3.4	0.9		
6	Implied excess demand as a result of power shortages, TJ	3.6						12.1	3.3		
7	**Excess carbon dioxide emissions as a result of power shortages, tonnes**	74.1						**898**	**242**		
8	Predicted diesel generation in 2015, 2016 based on 2014 demand, GWh							12.2	12.2		
9	Implied excess demand as a result of power shortages, GWh							4.6	3.5		
10	Implied excess demand as a result of power shortages, TJ	3.6						16.6	12.6		
11	**Excess carbon dioxide emissions as a result of power shortages, tonnes**	74.1						**1227**	**934**		

[9] There are circa 74 100 kg of carbon dioxide for every TJ of energy produced from diesel as published in the Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (Gómez *et al* 2006), IEA (2019).

[10] 1 GWh of energy is equivalent to 3.6 TJ of energy (IEA 2019).

in both Lusaka and the Copperbelt; 50/84.1 = 59%). In fact, 71% of the sample came from Lusaka.

We calculated CO_2 emissions emanating from diesel generation over months in drought years and months in non-drought years by manufacturing firms following these steps:

1. Nine firms either provided information of MJ of energy produced by diesel generation/month or litres of diesel consumed in power generation over the years 2015–2018. For the firms that provided information on litres of energy combusted, we converted these into energy values using publicly available conversion factors for litres of diesel combusted into energy.[8] We then converted energy yielded from diesel generation into CO_2 emissions using publicly available conversion factors for energy generated from diesel generation.[9]

2. These nine firms also provided their subsector, kVA of installed diesel generator capacity and 6 provided their installed diesel generator capacity in litres. We therefore ran ordinary least squares regression with CO_2 emissions as the dependent variable and the following variables as independent variables:

CO_2 emissions = a * year of drought[10] + b * installed capacity expressed in kVA + c * installed capacity expressed in litres + d * whether the firm is in the food subsector + constant.

3. We then multiplied the regression coefficients by the characteristics of the remaining firms, 91 of which had generators, of which 84 provided kVA installed diesel generator capacity values and 41 provided litres of installed capacity. All firms provided information on their subsector.

4. Results and discussions

4.1. ZESCO's energy generation using diesel
Table 5 row 1 shows the total energy generation by ZESCO using diesel. Energy generation using diesel increased by a compounded annual growth rate of 10% (see row 3) from 2010 to 2014, although growth from 2013 to 2014 of 3% (see row 2) suggests that it was plateauing.

If we ignored this plateauing and used the CAGR for 2010 to 2014, row 5 shows the implied excess diesel generation attributable to low hydropower reservoir levels in 2015 and 2016; row 6 shows the same but in TJ and row 7 converts this into carbon dioxide emissions.

Taking into account the plateauing, if we assume ZESCO's diesel generation would not have increased past its 2014 consumption level but for the drought that effected power outages in 2015 and 2016, row 8 shows what the energy produced by diesel generation would have been, row 9 calculates the implied excess attributable to low reservoir levels, row 10 shows the same in TJ and row 11 converts this into carbon dioxide emissions.

Due to low hydropower dam reservoirs in 2015 and 2016, the emissions emanating from increased used of diesel generators by ZESCO could have been as high as 1230 tonnes of CO_2 (100 tonnes/month).

4.1.1. The mining sector
Row 3 of table 6 bears out our prediction that Zambia's mining energy use patterns are predictable. For each of 2013, 2016, 2017 and 2018, mining's grid-electricity intensity was 7.8 GWh/1000 tonnes of copper.

Using this average grid electricity intensity with the copper produced for each of the years, we computed the predicted grid electricity consumption for each year (row 5). Where the predicted grid electricity consumption was greater than the actual grid electricity consumed, the variance was noted in row 6. We see a great deal of variance in 2016—the second year of power outages in Zambia.

We can plausibly infer that Zambia's mining sector self-generated 47 GWh of energy in 2016, and that up to 100% was generated from diesel generators. Zambia's mining sector would in an average month in 2016 have contributed to 1000 tonnes of carbon dioxide.[11]

4.1.2. Households
Two-thirds of households in the highest income bracket reported using diesel generators when grid power went out, 30% of households reported using diesel generators in the next highest income bracket (see figure 2 below).

Five households that used generators provided information on their installed capacity in kVA, the median of which was 5kVA. At a power factor of 0.8, this is the equivalent of 4 kW. Owners generally used their generators after sunset (6pm) for an average of 5 h.[12] This implies that the respondents used their generators until they slept at approximately 11pm. Our sample of installed kVA and hours of generation use was not large enough to regress against household income given the limited richness in data. However, our sample of 47 households that reported both their

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[8] 38.29 MJ/litre of diesel fuel consumed (U.S. Energy Information Administration 2019).

[9] Gómez *et al* (2006, table 2.2).

[10] 2015 and 2016 were years of drought; 2017 and 2018 were not.

[11] 1 GWh of energy is equivalent to 3.6 TJ of energy (IEA 2019) and there are circa 74 100 kg of carbon dioxide for every TJ of energy produced from diesel (Gómez *et al* 2006).

[12] Treating the 20 h response as an outlier, the average of five responses was 4 h of a power outage before respondents switched on their generators. The average duration of five responses was 5.2 h.

Table 6. Imputing diesel-generated electricity by the mining sector.

Row	Year	2013	2014	2015	2016	2017	2018
1	Mining grid electricity consumption, GWh	5929	5871	6246	5918	6202	6682
2	Copper (Cu) production, '000s tonnes	760	708	712	763	794	854
3	Grid electricity/Cu produced, GWh/'000 tonnes	7.8	8.3	8.8	7.8	7.8	7.8
4	Median average electricity/Cu produced, GWh/'000 tonnes	7.8					
5	Predicted grid electricity consumption given Cu produced, GWh	5941	5535	5566	5965	6207	6676
6	Variance where predicted grid electricity consumption > actual grid electricity consumed	12.4			46.9	5.3	

Sources: Energy Regulation Board of Zambia (2015, p 8, 2016, p 0, 2017, p 9, 2018, p 36, 2019, p 39) and U.S. Geological Survey (2015, 2016, 2017, 2018, 2019, 2020).
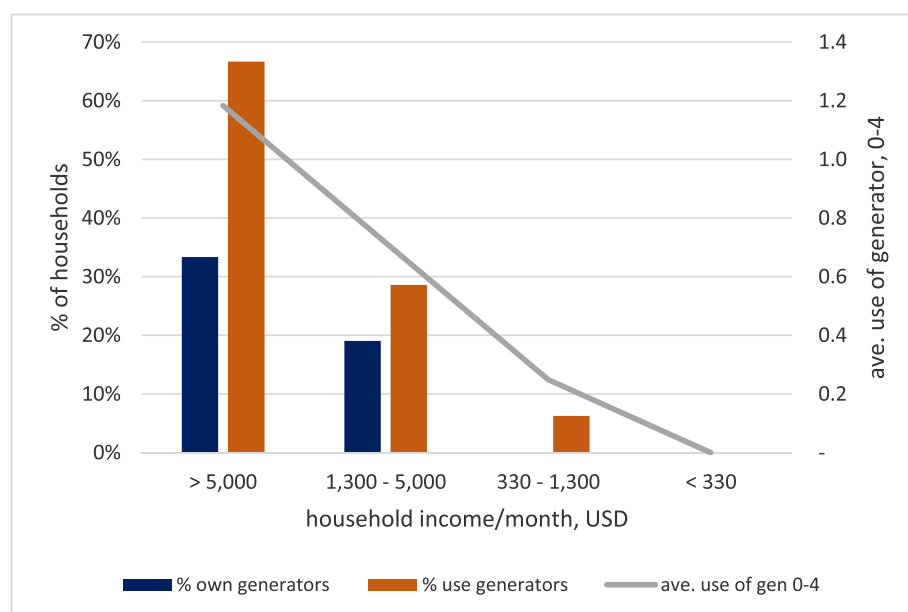
Figure 2. The percentage of households by income group that owned and used generators; the extent to which households used generators by household income.

Table 7. Indicators and measurements for household Tobit regression.

Indicator	Measurement
Dependent variable	
dieselgen	Extent to which household uses diesel generation: 0 = 'do not use' 1 = 'use a bit' 2 = 'use to a moderate extent' 3 = 'use to a major extent' 4 = 'rely upon all the time'
Independent variable	
Zmkmonth	Household income, Zambian Kwacha/month

Table 8. Tobit regression of household income on extent to which diesel generation is used and on diesel generator ownership.

Variables	dieselgenuse (0–4)
Zmkmonth	0.0000254**
	(8.28e-06)
Constant	−0.866113
	(0.2199039)
Prob > chi2	0.0035
Regression	Tobit
Observations	47

Coefficients first, standard errors in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

household income bracket and their subjective extent of generator use was (see table 7).

Because our dependent variable was ordinal, we used Tobit regression analysis on income as the independent variable, which was statistically significant and had a positive effect on generator use at the 5% level. The Chi-square of the model was also statistically significant at the 5% level as shown in table 8. The interpretation of the coefficient was that every additional kwacha of income earned per household per month resulted in extra use of the diesel generator by 0.0000254 units on the scale of 0 to 4. This means that the Tobit regression model predicts that the highest income bracket used generators on average 1.2 ('use a bit') and the second highest income households were using them on average 0.7 (less than 'a bit') contrasting with the average usage of 1.7 for the highest income bracket and 0.8 for the second highest income bracket (see figure

2 above). What this effectively means is that households in the highest income bracket were using generators 160% more than households in the second highest income bracket, in which we can expect to find the median installed capacity of power generation and median duration of hours of generator use (see the third column of table 9).[13] Households in the next income bracket use generators diesel generation 35% of the level that households in the second highest income bracket do. These results are shown in columns 5 and 6 of table 9 below. Household carbon dioxide emissions from diesel generation were approximately 2900 tonnes in the worst months of 2019.

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[13] Demographic data was sourced from Zambia's 2012 Labour Force Survey (Zambia Institute for Policy Analysis & Research 2013), and the exchange rate for 2012 was worked out comparing local currency current GDP with current GDP expressed in USD (World Bank 2020b).

Table 9. Estimate of the number of Zambian households that use a diesel generator.

monthly hh income, USD	% use generators	households	hh using generators	generator intensity use, 0–4	% relative use	TJ/month	tonnes CO2
>5000	67%	10 000	6667	1.2	164%	18.88	1399
1300–5000	29%	40 000	11 429	0.7	100%	19.75	1463
330–1300	6%	20 000	1250	0.3	35%	0.75	56
<330	0%		—	0.1	8%	—	—
			19 345			39	2918
0.0000636	coefficient of use for every ZMK/month			30	d/m		
4	average hours/day of generator usage			74 100	kg CO2/TJ of diesel energy		
4	average kW size of generator used/hh			3.6	TJ/GWh		

Table 10. Ranking of the years 2014–2018 for worse manufacturing production losses on a scale of 0–4.

Year	2018	2017	2016	2015	2014
Sum of 0–4 responses	47	66	92	73	40
Number of responses for year	42	42	38	32	25
Average score for year	1.12	1.57	2.42	2.28	1.60
Ranked in terms of worst year	5	4	1	2	3

Source: Manufacturing survey.

4.1.3. Manufacturing firms

We found that more than 73% of firms had acquired use of a backup generator, and that 52% of these had bought their oldest generators in the years of Zambia's worst power outages in 2015 and 2016 (see figure 3).

If the age of the oldest generators on firms' premises can be taken as a proxy for the first time that firms bought their generators, then the data on which Farquharson *et al* (2018) based their top-down analysis of generator emissions for Zambia, at least, was out of date because it was collected by the World Bank from December 2012-February 2014 (World Bank and International Finance Corporation 2014). The purchase year of firms' oldest generators was directly observable by enumerators and did not rely on institutional memory which is vulnerable to change in personnel and wrongly remembered events.

For the years 2014 to 2018, we asked respondents to rank them on a scale of 0 to 4 for losses. 0 represented no losses in production, 1 represented 1%–15% losses of targeted production, 2 represented 16–30%, 3 represented 31%–50% losses and 4 represented more than 50% of losses. To account for the greater number of responses for the most recent years, the aggregate score for a given year was divided by the number of responses for that year. 2016 and 2015 ranked as the worst years (see table 10). Surviving firms reported losses towards the higher spectrum of 16%–30% in 2015 and 2016.

Supporting our finding that more than 80% of firms that saw reduced revenues as a result of power outages is the 97% correlation between the average scores for losses for 2014 to 2018 with the number of oldest generators firms had that were purchased in the years 2014 to 2018 (see figure 4).

93% of firms that had had access to a generator and whose generator did not break down continued to use their generator.

From nine firms that provided detailed accounts of the extent of energy then had generated from diesel generators or litres of diesel they had consumed in generating energy on a monthly basis over 2015–2018, we calculated the emissions associated with

Table 11. Indicators and measurements for manufacturing ordinary least squares regression.

Indicator	Measurement
Dependent variable	
maxCO2	Maximum carbon dioxide emissions in a month, kg
Independent variables	
year2015_2016	Drought year or not. 1 = 2015 or 2016, 0 = 2017 or 2018
kva	Aggregate of diesel generator capacity owned by firm, kVA
litrecapacity	Aggregate of diesel generator capacity owned by firm, litres
food	Manufacturing subsector. 1 = food & beverages subsector, 0 = other subsector

Table 12. Predictors of maximum kg of CO_2 emitted in a month.

VARIABLES	(1) maxco2
year2015or2016	44 862* (4749)
Kva	17.88** (0.697)
Litrecapacity	16.95* (2.218)
Food	−35 702 (6905)
Constant	−6000 (4017)
Observations	6
Prob > F	0.0415
R-squared	0.999

Coefficients first. Standard errors in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Source: Manufacturing survey.

their diesel generation and ran these as dependent values in an OLS regression against four independent variables: installed generator capacities in kVA and litres, the years in which they ran their generators and their subsectors. The first three were statistically significant predictors. If the diesel generator was used in a drought year, CO_2 emissions for the month would be 45 000 kg greater. Each additional kVA of installed capacity translated into 18 kg of additional CO_2 emitted and each additional litre of installed capacity translated into an additional 17 kg of CO_2. We did not find statistical significance for various subsectors in our sample size which limited the number of subsectors that were observed (most belonged to the food and beverages subsector). Nevertheless, the R-squared of the model showed that the OLS regression model explained 99.9% variance in the dependent variable and because the p-value of the associated F-value of the model is less than 5%, we can say that the independent variables reliably predict the dependent variable.

Using the coefficients in table 12 above, we predicted emissions for Zambian manufacturing firms
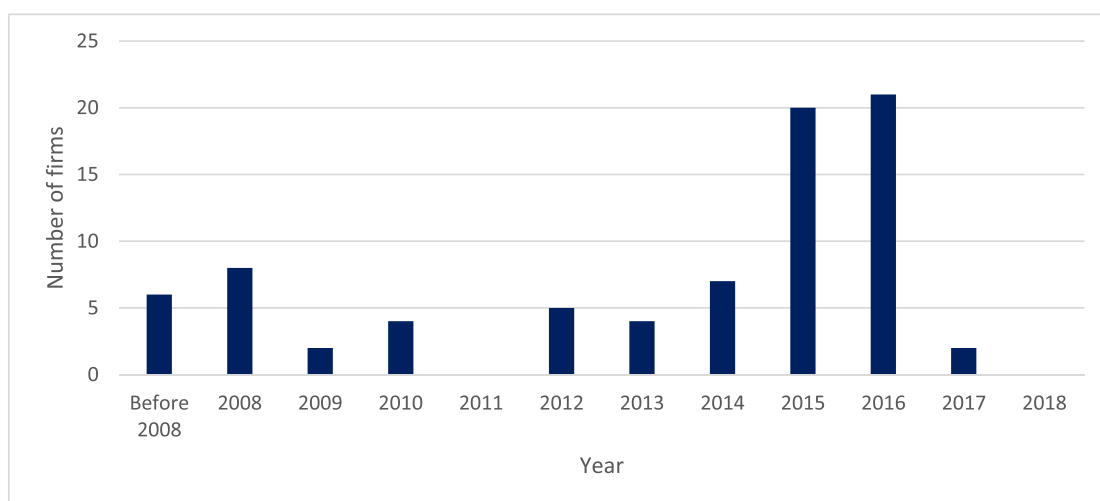
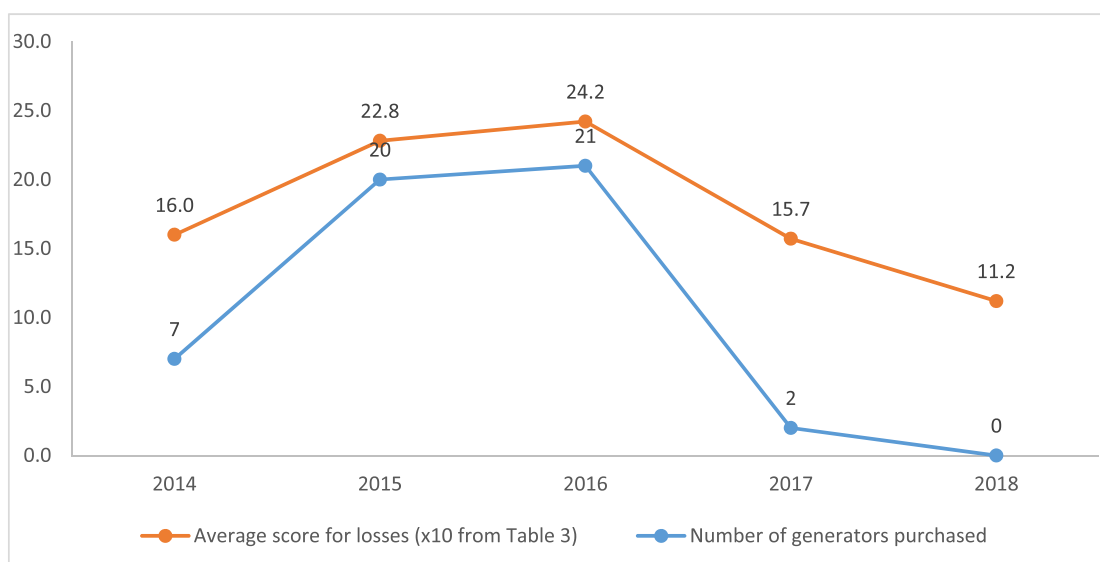**Figure 3.** Year in which first generator in use was purchased.

Figure 4. There is 97% correlation between the score of losses in a given year between 2014–2018 and the number of firms that have their oldest generators purchased in those years.

Table 13. Diesel generated CO2 emission (tonnes/month) from Zambia's power utility and major clients due to low hydropower reservoir levels.

Year	2015	2016	2019	projected for 2019
High end estimate CO2 emissions, tonnes/month				
ZESCO	102	78		
Mining sector		1045		1959
Households			2918	2918
Manufacturing firms	12 000	12 000		22 500
				27 377
hours of outages/day	8	8	15	

for which we collected data on the level of installed capacity of backup generation in terms of kVA and litres, as explained in the methodology above. Extrapolating the results for 123 such firms, the sum of CO_2 emissions from backup generation came out to

3800 tonnes for the worst month in 2015/2016 and 850 tonnes for the worst month in 2017/2018.

If there are the same number of manufacturing firms (390) as there were in 2014 (Ministry of Commerce Trade and Industry 2014) and the sample is

Table 14. Energy Regulation Board data tells a story of both decreased power output and an implied increase in technical and non-technical losses.

Zambia's energy crisis in 2015 and 2016—decrease in production, increase in energy losses resulting in increased imports	2013	2014	2015	2016	2017	% drop in 2016 from 2014
1—Energy output from all sources, GWh	13 299	14 453	13 440	11 696	15 195	19%
a—Kariba North	4507	4999	4316	2964	2689	41%
b—Kafue Gorge	7463	6666	6417	5853	7363	12%
c—Kariba North Bank Extension		1162	1179	672	599	42%
d—Victoria Falls	810	811	785	754	684	7%
2—Net exports, GWh	1010	1243	391	− 1391	310	−16 708%
a—Imports, GWh	73	13	785	2185	753	
b—Exports, GWh	1083	1256	1176	794	1063	37%
3—Domestic energy consumption, GWh	10 846	12 405	11 450	10 858	12 192	
Annual growth in energy consumption		14%	−8%	−5%	12%	
4—Output—(exports + domestic consumption), GWh	1370	792	814	44	1940	
5—Output—(net exports + domestic consumption), GWh	1443	805	1599	2229	2693	
6—Implied unused generated energy, % = 5/1	11%	6%	12%	19%	18%	
7—lost energy, GWh	1443	805	1599	2229	2693	
8—Difference in energy consumption between 2014 and 2015/2016			955	1547		

Sources: Energy Regulation Board of Zambia (2015, 2016, 2017, 2018).

representative of the population (which table 4 suggests it is), then the emissions calculated for 123 firms can be extrapolated by multiplying the emissions figures by 390 and dividing by 123 to yield the results of 2700 tonnes for 2017/2018 and 12 000 tonnes for the worst month in 2015/2016.

4.1.4. Aggregate results

Altogether CO_2 emissions from backup generation would have been 100 tonnes a month by ZESCO in 2015, 1000 tonnes in the worst months of 2015/2016 for the mining sector, 1700 tonnes in the last months of 2019 for households and 12 000 tonnes in the worst months in 2015/2016 for large manufacturing firms.

As noted earlier, the number of daily hours of outages apparently doubled for load shedding from 8 in 2015 to 15 at the end of 2019 (Energy Regulation Board of Zambia 2016, Zesco 2019). It is therefore probable that mining firms and manufacturing firms would have been even worse hit with power outages in 2019 during their hours of operation. Depending on their ability to finance extra diesel generation and how squarely the outages fell during their hours of operation, emissions could have increased by up to 100%. The range for CO_2 emissions from diesel generators from these three sectors at the end of 2019 from Zambia's power outages could therefore have been as high as 27 000 tonnes of CO_2/month. We will be able to calculate the emissions from ZESCO's diesel power plants in 2019 when the Energy Regulation Board publishes its report for 2019.

4.2. Uncertainty analysis

Finance and property overtook the manufacturing subsector as the third largest consumer sector of ZESCO electricity in 2016. We were unable to estimate backup diesel generation emissions for this sector. We do not expect it to have contributed to emissions to the same extent as energy-intensive manufacturing firms would have, but would have expected this sector to have been more energy-intense than ZESCO's high-income households since client-focused professional service sector offices cannot afford to not have power outages during office hours.

Given that new power plants were also coming online for ZESCO and the fluctuating capacity utilisation rates for its existing hydropower assets, we also did not feel confident in predicting how much energy shortfall ZESCO would have tried to make up using diesel generation in 2019.

There was significant sensitivity (resulting in 26 000 tonnes/month for the aggregate result versus 27 000 tonnes/month) in the currency conversions and salary escalations we assumed from 2012 Zambian kwacha to December 2019 United States dollars for the purpose of figuring out how many households existed in each of the higher middle class income brackets according to Central Statistical

Office Labour Force Survey data (Zambia Institute for Policy Analysis & Research 2013).

5. Conclusion

As noted earlier, Farquharson *et al* (2018) used out-of-date data for their model. For Zambia, they estimated that a typical month saw 5.2 outages for an average of 2.8 months; that the installed grid capacity was 2.3 GW and that generator availability was 3% of the grid. This would imply that they estimated that generators on average produced 1 GWh of energy in a month, the equivalent of 3.6TJ, resulting in just 74 tonnes of CO_2. This is not close to the same level of magnitude of emissions that we estimated for just one sector of the economy.

To triangulate our results, therefore, we need to perform our own estimates using more realistic high-level data for a back of the envelope ratification that Farquharson et al's study does not provide. 2018 saw 13 000 GWh of grid electricity consumed in Zambia (see table 1). A twelfth of that is 1100 GWh in a month. 15 h a day of outages would imply that most of a work day or an evening at home post-sunset would require a generator for the 33% of Zambia's population that enjoy on-grid connections. If we assumed that generators covered 15% of grid capacity for a country with an established mining industry that consumes more than half of grid-electricity, and that generators were used for half the time that there were power outages, CO_2 emissions would be 22 000 tonnes. By this calculation, our bottom-up approach estimate seems reasonable.

Our bottom-up analysis suggests that the manufacturing sector uses diesel generators more intensively than the other sectors that consume more energy than it does. From ZESCO's load shedding schedule of October 2019, we can see that ZESCO is attempting to minimise disruption to manufacturing firms during business hours (Zesco 2019). This is a good idea. ZESCO is also installing increased power generation capacity (Zesco Ltd 2017b). However it is doing this through hydropower which will continue to fail in times of drought and through emissions-intensive coal-fired power. We have a couple of alternative suggestions for ZESCO.

First, ZESCO should consider prioritising clients that use backup diesel generation the most for more reliable energy. To achieve this end, ZESCO should look into the feasibility of sourcing these clients' energy from the SAPP's nuclear thermal station.

Second, ZESCO should seek to dampen inefficient energy use. It could do this by increasing average tariffs across the board, which would also help it achieve system sustainability so that it can invest in increased installed power generation capacity or afford the cost-recovery tariffs charged by energy exporters on the SAPP. Beyond increasing tariffs across the board, ZESCO could also increase

specific tariffs. It could increase the peak tariffs to decrease peak demand. Research by Ahmed *et al* (2019) showed that manufacturing firms use more peak-hour energy than predicted because peak energy was under-priced. Increasing the price of peak energy would reduce demand for peak energy, if the tariff is increased sufficiently so that demand elasticity becomes negative against price increases. Another mechanism for dampening inefficient energy use would be for ZESCO to charge a penalty for reactive power.

Third, ZESCO and the Energy Regulation Board should investigate ZESCO's elevated sources of distribution and transmission losses and work to address these before commissioning extra power supply. ZESCO's transmission and distribution losses were recorded as 10% (Energy Regulation Board of Zambia 2017, p 63) according to self-reported data by ZESCO. An Energy Regulation Board official noted that this was too good for the kind of data his agency was able to extract from what they were given by ZESCO. The implied losses of generated energy grew to almost a fifth of energy generated in 2016, calculated by subtracting from the output generated the net exports and domestic consumption and dividing that by the output generated (see table 14 below)—well above the 12% threshold below which ZESCO is required to maintain distribution losses. This could be the result of both transmission losses and non-technical losses, such as pilfering and unmetered use. ZESCO economists said that these

calculations in line 6 of the below table were credible calculations (personal communication, 3 September, 2019, ZESCO Ltd, Lusaka). The transmission and distribution losses in 2015 and 2016 were greater than the difference in domestic energy consumption between 2014 and 2015 and 2014 and 2016 respectively.

In terms of reliable supply to meet Zambia's demonstrated demand for grid electricity, cross-continental super-grids could be the answer. With the right governance structures in place to prevent hold-ups and renegotiations, they would allow the transfer of energy from jurisdictions with surplus low-greenhouse gas energy generation infrastructure to jurisdictions with deficient energy generation infrastructure. Within the SAPP, the Koelberg nuclear power station in South Africa provides dependable baseload energy that is emissions-free during operation, but its capacity is insufficient to power all of southern Africa and reports of corruption behind the additional procurement of nuclear power (Cornish 2019) have not been confidence inspiring. Namibia has enormous solar potential, though without better battery storage, intermittency will remain an issue. Tanzania and Mozambique's natural gas may do almost the same harm as Zambia's coal (BEIS 2019, table 4) for climate change when well-to-tank methane leakages are taken into account (Marchese and Zimmerle 2018) but the immediate effects of their emissions on human health would be less deleterious. Beyond the SAPP and beyond Africa's intermittent or climate vulnerable renewable energy potential are France's nuclear power plants.

To the extent that Zambia's demonstrated demand for grid electricity is an under representation of demand by those without grid connections, and to the extent that energy cannot be so easily transferred across continents to prevent emissions from the construction of power plants and the destruction of carbon sinks, the next solution requires even greater political will. If populations privileged with power want to prevent a proliferation of fossil-fuel plants in hydropower dependent countries falling prey to anthropogenic climate change-induced drought, they should welcome the orderly immigration of people from those countries.

The case of reduced hydropower capacity in Zambia is unfortunately not a unique one. Up to a fifth of the global population live in nations heavily dependent on hydropower that is vulnerable to drought due to increases in average global temperatures. The above suggestions for how Zambia can overcome its energy challenges in a low greenhouse gas intensive manner could therefore have broader applicability.

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References

Ahmed I 2020 The cost of power outages to Zambia's manufacturing firms, households and the climate *Grid Reliability and Utility Operations*

Ahmed I, Baddeley M, Coffman D M, Meikle J, Oseni M and Sianjase G 2019 The cost of power outages to Zambia's Manufacturing firms *Report* F-41408-ZMB-1 International Growth Centre

Barrick Gold Corporation 2019 *Lumwana* Barrick Website (available at: https://www.barrick.com/operations/lumwana/default.aspx)

Bata Z 2016 *Annual financial statements for the year ended 31 December 2015*

Bata Z 2017 *Annual Report 2016*

Bayliss K and Pollen G 2019 *From Global to Local: Exploring the effects of the global energy policy paradigm in Zambia* (No. 119; SRI Papers, Issue 119) (available at: https://sri-working-papers.leeds.ac.uk/wp-content/uploads/sites/67/2019/10/SRIPs-119.pdf)

BEIS 2019 *2019 Government Greenhouse Gas Conversion Factors for Company Reporting. Methodology Paper for Emission Factors* (Issue August) (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/829336/2019_Green-house-gas-reporting-methodology.pdf)

British American Tobacco 2016 *Audited Financial Results For the Year ended 31 December 2015* (Issue February)

British American Tobacco 2017 *Annual Report & Financial Statements for the year ended 31 December 2016*

Cantore N, Clara M, Lavopa A and Soare C 2017 Manufacturing as an engine of growth: which is the best fuel? *Struct. Change Econ. Dyn.* **42** 56–66

Cornish -J-J 2019 South Africa scraps Russian nuclear plant plans *Radio France International* (available at: www.rfi.fr/en/africa/20190824-south-africa-cancel-russia-nuclear-plant-order-economy-ramaphosa)

Deemer B R, Harrison J A, Li S, Beaulieu J J, Delsontro T, Barros N, Bezerra-Neto J F, Powers S M, Dos Santos M A and Vonk J A 2016 Greenhouse gas emissions from reservoir water surfaces: A new global synthesis *BioScience* **66** 949–64

Energy Regulation Board of Zambia 2015 *Energy Regulation 2014*

Energy Regulation Board of Zambia 2016 *Energy Sector Report 2015* (available at: www.erb.org.zm/reports/EnergySectorReport2014.pdf)

Energy Regulation Board of Zambia 2017 *Energy Sector Report 2016* (Issue May) (https://doi.org/10.13140/RG.2.1.3893.7043)

Energy Regulation Board of Zambia 2018 *Energy Sector Report 2017* (available at: www.erb.org.zm/downloads/reports/esr2017.pdf)

Energy Regulation Board of Zambia 2019 *Energy Sector Report 2018* (available at: www.erb.org.zm/reports/esr2018.pdf)

FAO 2015 *FAO and El Niño* Food and Agriculture Oganization of the United Nations (available at: www.fao.org/el-nino/en/)

FAO 2018 *El Niño* Food and Agriculture Organization of the United Nations (available at: www.fao.org/emergencies/crisis/elnino-lanina/intro/en/)

Farquharson D, Jaramillo P and Samaras C 2018 Sustainability implications of electricity outages in sub-Saharan Africa *Nat. Sustainability* **1** 589–97

First Quantum Minerals Ltd 2019 *Kansanshi* First Quantum Minerals Website (available at: www.first-quantum.com/Our-Business/operating-mines/Kansanshi/)

Geological Survey U S 2015 *Mineral Commodity Summaries 2015* (available at: https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/copper/mcs-2015-coppe.pdf)

Gómez D R, Watterson J D, Americano B B, Ha C, Marland G, Matsika E, Namayanga L N, Osman-Elasha B, Saka J D K and Treanton K 2006 Chapter 2 Stationary Combustion *2006 IPCC Guidelines for National Greenhouse Gas Inventories Vol. 2 Energy*, ed A Garg and T Pulles (Institute for Global Environmental Strategies)

Hao Z, Hao F, Singh V P and Zhang X 2018 Quantifying the relationship between compound dry and hot events and El Niño – southern Oscillation (ENSO) at the global scale *J. Hydrol.* **567** 332–8

IBRD and IDA 1970 *Appraisal of Kariba North Hydroelectric Project Zambia* (available at: http://documents.worldbank.org/curated/en/917071468334477402/pdf/multi-page.pdf)

IBRD and IDA 1973 *Appraisal of Kafue Hydroelectric Project (Stage II) Zambia* (available at: http://documents.worldbank.org/curated/en/824421468167973026/pdf/multi-page.pdf)

IEA 2019 *Emission Factors 2019 Database Documentation* (available at: http://wds.iea.org/wds/pdf/CO2KWH_Methodology.pdf)

Jourdan P P 1990 *Strategies for the Regional Planning of the Minerals Industry in Southern Africa: the case of the SADCC* (University of Leeds) (available at: http://etheses.whiterose.ac.uk/490/1/uk_bl_ethos_291037.pdf)

Konkola Copper Mines Plc. 2019 *Corporate Profile* Konkola Copper Mines Website (available at: http://kcm.co.zm/corporate-profile/)

Malunga J 2019 Consumers' maximization-of power worsening load-shedding - Kapata *News Diggers!* (available at: https://diggers.news/local/2019/10/01/consumers-maximization-of-power-worsening-load-shedding-kapata/)

Mar L E 2009 *Carbon impact of proposed hydroelectric dams in Chilean Patagonia* (Massachusetts Institute of Technology) (available at: https://dspace.mit.edu/handle/1721.1/53068)

Marchese A J and Zimmerle D 2018 The US natural gas industry is leaking way more methane than previously thought. Here's why that matters *The Conversation* (available at: https://theconversation.com/the-us-natural-gas-industry-is-leaking-way-more-methane-than-previously-thought-heres-why-that-matters-98918)

Mfula C 2010a First Quantum's Zambia mine hit by power outage *Reuters* (available at: www.reuters.com/article/update-2-zambia-mining-power-idAFLDE6180X820100209)

Mfula C 2010b Singapore firm to spend $108 mln on Zambia coal mine *Reuters* (available at: https://uk.reuters.com/article/mining-zambia-singapore-firm-to-spend-108-mln-on-zambia-coal-mine-idUKLDE67K09320100821)

Ministry of Commerce Trade and Industry 2014 *Manufacturing Sector Study Report: 2011-2012* (Issue August)

National Breweries 2016 *Annual Report 2015*

News S. (2011). Konkola Copper Mines to invest USD 33 million for diesel generators *Steel Guru* (available at: https://steelguru.com/steel/konkola-copper-mines-to-invest-usd-33-million-for-diesel-generators/242497)

Park S F 1968 *Basic Data on the Economy of Zambia* (available at: https://play.google.com/books/reader?id=K_ZhUrU5lfoC&hl=en_GB&pg=GBS.PA1)

Sichone Y M, Mulenga P, Phiri C, Kapena S and Fandamu H 2016 Electricity load shedding : an econometric analysis of the productivity of firms in the manufacturing sector in Lusaka **2** 151–7

Steinbuks J and Foster V 2010 When do firms generate? Evidence on in-house electricity supply in Africa *Energy Econ.* **32** 505–14

Sugar Z 2016 *2015 Annual Report*

Sugar Z 2017 *2016 Annual Report* (available at: https://africanfinancials.com/document/zm-zmsg-2016-ar-00/)

Syndigate 2011 KCM deploys 3 diesel generators at Konkola Deep Mining Project *MENA Report* (available at: https://search-proquest-com.libproxy.ucl.ac.uk/docview/872316305?rfr_id=info%3Axri%2Fsid%3Aprimo)

Szirmai A and Verspagen B 2015 Manufacturing and economic growth in developing countries, 1950-2005 *Struct. Change Econ. Dyn.* **34** 46–59

Tembo B 2018 *Strategic investment decisions in Zambia's mining sector under a constrained energy system* (Issue January) (University College London) (available at: https://discovery.ucl.ac.uk/id/eprint/10048151/)

U.S. Energy Information Administration 2019 *Calculators for energy used in the United States* Energy Explained (available at: www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php)

U.S. Geological Survey 2016 *Mineral Commodity Summaries 2016* (available at: https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/copper/mcs-2016-coppe.pdf)

U.S. Geological Survey 2017 Mineral Commodity Summaries 2017 *Mineral Commodity Summaries* (available at: https://s3-us-west-2.amazonaws.com/prd-wret/assets/

palladium/production/mineral-pubs/copper/mcs-2017-coppe.pdf)

U.S. Geological Survey 2018 Mineral Commodity Summaries 2018 *Mineral Commodity Summaries* (available at: https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/copper/mcs-2018-coppe.pdf)

U.S. Geological Survey 2019 Mineral Commodity Summaries 2019 *Mineral Commodity Summaries* (available at: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-coppe.pdf)

U.S. Geological Survey 2020 *Mineral Commodity Summaries 2020* (available at: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-copper.pdf)

Vidal J 2016 El Niño is over – but it leaves nearly 100 million people short of food *The Guardian* (available at: www.theguardian.com/global-development/2016/may/30/el-nino-is-over-but-it-leaves-nearly-100-million-people-short-of-food)

Wang G, Cai W, Gan B, Wu L, Santoso A, Lin X, Chen Z and Mcphaden M J 2017 Continued increase of extreme El Niño frequency long after 1. 5 ° C warming stabilization *Nat. Clim. Change* **7** 568–72

World Bank and International Finance Corporation 2014 Zambia Country Profile 2013 *World Bank: Vol. Enterprise* (Issue April)

World Bank 2018a *World Bank projects and operations in Zambia* World Bank 10.1007/s10461-016-1645-x

World Bank 2018b *Zambia precipitation 1991-2015* Climate Change Knowledge Portal, World Bank Group (available at: http://sdwebx.worldbank.org/climateportal/index.cfm?page=downscaled_data_download&menu=historical)

World Bank 2020a *Electricity production from hydroelectric sources (% of total)* (available at: https://data.worldbank.org/indicator/EG.ELC.HYRO.ZS?view=chart)

World Bank 2020b *GDP (constant LCU)* (available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.KN)

World Bank 2020c *Zambia Trade Summary 2018 Data* World Integrated Trade Solution (available at: https://wits.world bank.org/CountryProfile/en/Country/ZMB/Year/LTST/Summary)

World Bank 2020d *Zambia World Development Indicators*

Zambeef Products 2017 *Annual Report 2016*

Zambeef Products 2018 *Annual Report 2017*

Zambezi River Authority 2019 *Lake Kariba Weekly Levels in Meters* Lake Levels (available at: www.zambezira.org/hydrology/lake-levels)

Zambia Chamber of Mines 2016 *A concentrated mining sector* Mining for Zambia (available at: https://miningforzambia.com/a-concentrated-mining-sector/)

Zambia Institute for Policy Analysis & Research 2013 *The Distribution of Household Income and the Middle Class in Zambia* (No. 14; Issue December) (available at: www.zipar.org.zm/research/our-publications/working-papers/72-the-distribution-of-household-income/file)

Zambia L 2016 *Annual Report 2015*

Zambia L 2017 *Annual Report 2016*

ZAMEFA 2016 *Directors ' Report and Financial Statements For the year ended 31 December 2015*

ZCCM Investment Holdings Plc 2019 *Mopani Copper Mines PLC* ZCCM-IH Website (available at: https://zccm-ih.com.zm/copper-cobalt-gold/mopani-copper-mines/)

Zesco Ltd 2017a *Current Zesco Tariffs* Zesco Website (available at: www.zesco.co.zm/customerCare/tariffs)

Zesco Ltd 2017b *Zesco's planned additional energy generation* (Zesco Ltd.)

Zesco 2019 *Countrywide Load-Shedding Schedule October 2019 Revised* available at: www.zesco.co.zm/customerCare/loadSheddingSchedule)

ZICTA and CSO 2018 *2018 National Survey on Access and Usage of Information and Communication Technologies by Households and Individuals - A Demand Side Assessment of Access and Usage of ICTs in Zambia* (available at: https://www.zicta.zm/Downloads/publications/2018ICTSurvey_Preliminary Report.pdf)